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NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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REPORT NO. 941

VARIOUS MEASURES OF THE EFFECTIVENESS OF YELLOW GOGGLES

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Naval Medical Research and Development Command
Research Work Unit MF58.524.013-1039

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SUMMARY PAGE

PROBLEM

To determine whether specific visual functions other than acuity might be improved by the use of yellow goggles.

FINDINGS

Performance using yellow goggles and neutral goggles matched for luminous transmittance was tested in the laboratory. Yellow goggles improved both the perception of the depth of low contrast contours and the time required to respond to low contrast patterns.

APPLICATIONS

These results will be tested in field conditions of low visibility and "white-out" due to snow, to determine if yellow goggles provide a reasonable aid for cold weather operations.

ADMINISTRATIVE INFORMATION

This investigation was conducted as part of the Naval Medical Research and Development Command Work Unit MF58.524.013-1039 - "Improvement of vision and orientation under white-out conditions." It was submitted for review on 29 Aug 1980, approved for publication on 2 Oct 1980 and designated as NSMRL Report No. 941.

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OVERVIEW

Military operations in the cold regions of the world are frequently hindered by loss of visibility due to weather conditions. Problems can be particularly severe in snow-covered terrain where poor lighting, loss of contrast, and fogs, snow, and "white-out" contribute. A technique which is widely used to improve vision under these conditions is the use of yellow goggles. Skiers commonly don yellow goggles during snow storms or in the flat lighting conditions at the end of the day. Similarly climbers use the dark yellow or "glacier" goggles when travelling in high altitude, bright, snow-covered conditions. The popularity of yellow, however, has been a paradox to visual scientists for there have been many studies since the days of World War II, that have shown that visual acuity with yellow goggles is no better than with any other color or neutral, as long as the overall light levels are equated.

Recent advances in understanding the physiology of human vision, however, have suggested a possible cause for the paradox. Briefly, the theory states that for some visual functions, the output of three different types of cones is combined additively, while for others the output of one type of cone is subtracted from that of another. Thus for the first type of function, the color of the stimulating light does not matter and the more light the larger the response. For the second type, however the presence of more than one color may cause an inhibitory effect and the response may be smaller even though more light is present. Thus yellow goggles in eliminating the inhibitory or subtractive blue input, could result in a physiologically stronger signal. Furthermore, any visual function mediated at least in part by the opponent system could be improved by yellow goggles. This research represents a search for the visual functions which might be involved; both practical considerations and theoretical implications were considered in the choice of functions to be measured. Results from four different laboratory studies are presented.

Two of the studies were of depth perception, since skiers believe that yellow goggles help them perceive depressions and moguls in the snow. The perception of depth is not however a unitary process but a variety of visual mechanisms are involved. Stereoacuity, or the perception of depth based upon the disparate image seen by the two eyes was selected as the most important binocular mechanism and the perception of low contrast contours was chosen as an important monocular input. Five conditions were compared: no goggles, light yellow goggles, dark yellow "glacier" goggles, and light and dark neutral goggles whose transmittances match that of the yellows. The same ten subjects were tested under all five conditions.

The results showed that there were no differences between yellow and neutral goggles for stereoacuity but that there were significant improvements in the perception of low contrast contours with yellow.

Contrast sensitivity for targets of different sizes (spatial frequencies) was chosen as the other visual function to be measured. There is now considerable evidence that contrast sensitivity is an effective measure of human vision. For high spatial frequencies or very small targets, it encompasses the normal measurement of visual acuity, but it also gives information on sensitivities to targets of all sizes. Reaction time of the speed of response to the different sized targets was chosen for theoretical reasons.

The first study employed the same five goggle conditions as were used in the depth perception tests. Ten subjects responded to targets of sizes encompassing the range of human sensitivity. Comparison of yellow and luminance-matched neutrals showed that yellow yielded faster reactions for all except the highest spatial frequencies, where the two were equivalent. This, of course, is in agreement with the studies in the literature showing no improvement for acuity.

The second study investigated in more detail the lighting conditions, target sizes, and contrasts for which yellow is effective. Specifically these were low contrast targets in the middle of the range of spatial frequencies. The use of a white or a lighted surround theoretically should enhance the yellow advantage and it was shown to do so, adding a further explanation for the popularity of yellow goggles in snow-covered terrain.

INTRODUCTION

Yellow goggles have been widely used for certain outdoor activities, such as skiing and hunting, for many years and their popularity seems to grow. This presents a paradox to visual scientists, however, since dozens of experiments designed to test their effectiveness have shown no difference between yellow goggles and transmittance-matched neutral goggles. For example, Clark (1) surveyed 98 studies of tinted goggles and reported that the vast majority yielded negative results. Similarly Wyszecki (2) evolved a theory based on spectrophotometric differences which might have explained their popularity, but his elegant mathematical tests of this theory led him to conclude that no specific colored goggles would improve detectability.

Recent advances in understanding of the human visual system (3-7), however, have suggested a possible reason for the paradox. This paper presents experiments designed to test the implications of the theory and to explain the popularity of yellow goggles.

The Theory of Color Vision

Most modern theories of color vision are zone theories; that is, the outputs of three different kinds of cones are combined in different ways in later neural stages. Although the details of the various models differ (3-9), all agree on the existence of two different neural systems. In one, the signals from cones are combined linearly and the activity at higher neural levels can be predicted from the sum of the inputs; this system is the achromatic system. In the other, the outputs of one type of cone are antagonistic to, or subtracted from, the activity of another type of cone; this results in the red-green and the yellow-blue opponent systems and together they are referred to as the chromatic system. The evidence for such a theory comes from both electrophysiology, primarily from single cell recordings at a variety of locations within the monkey (macaque) visual system, (10-12) and from psychophysical experiments on human perception of color and brightness (3-9).

The theory has been particularly successful in explaining failures of additivity or of Abney's law. Abney's law states that the luminance of a mixture of differently colored lights is equal to the sum of the luminances of the components. This is an important law, as it serves as the basis for our definition of light, and it has been shown to hold in many experimental tests (13-16). However, failures of additivity for heterochromatic brightness matches have been known since the time of Helmholtz (17). If, for example, a red light and a green light are matched, one at a time, in brightness to a standard yellow light, and then one half of the red and of the green quantities are superimposed, the mixture no longer matches the yellow but is substantially darker. The successful explanation (6) assumes only that brightness is mediated by the output of both the achromatic and the chromatic systems. Since, with the chromatic system, the red and green are antagonistic, the sum is less than predicted from either in isolation. Conversely, when additivity is found to hold, as it does for flicker photometry (14) and for matches by the minimum border technique (13) the theory assumes the perception is mediated by the achromatic system only.

The achromatic-chromatic theory holds promise for explaining another visual phenomenon which has proved puzzling in the past: the increase in apparent brightness perceived when yellow goggles are worn. Since yellow goggles transmit only about 90% of the incident illumination, the world viewed through yellow goggles should be dimmer, if anything, but the universal judgment is that it appears clearly brighter. Early explanations invoked associations between yellow, sunlight and light but were never particularly convincing to the viewer. If, however, the perception of brightness does depend upon activity in both the chromatic and the achromatic systems, the elimination of the opponent (subtractive) component by the use of a yellow filter, could result in a physiologically larger response than the response without the filter.

Such theorizing has important practical applications. Yellow goggles, theoretically, could be effective for any visual perception mediated at least in part, by the chromatic system since the use of yellow reduces the inhibitory blue contribution.

A number of recent experiments have addressed the question of which system, achromatic or chromatic, underlies various perceptual phenomena; these include acuity (15,16,18), stereopsis (19), spectral sensitivity (9), reaction time (20), and duration thresholds (21). Since a basic difference between the achromatic and chromatic systems is whether the cone outputs add or subtract, tests for linear additivity (Abney's law) have been an important test of which system is active. Interestingly, almost all the previous, negative results comparing yellow goggles and luminance-matched neutrals, have employed acuity as the measure (1, 22) and acuity has been shown to behave in accordance with Abney's law (15,16); that is, its measurement can be predicted from the linear addition of light of different wavelengths. Thus the chromatic/achromatic theory predicts no advantage for yellow goggles.

This research then represents a search for visual functions which might be mediated by the opponent-color vision system and might therefore be improved by yellow goggles. Functions were selected for measurement because of practical considerations and theoretical implications.

EXPERIMENTS ON DEPTH PERCEPTION

Background

Since skiers routinely employ yellow goggles for specific lighting conditions (e.g., dull, snowy days or under flat lighting late in the day), and believe that they help in perceiving depressions and moguls, depth perception was an obvious choice. However, a number of different mechanisms, both monocular and binocular, are involved in the accurate perception of the third dimension and it was considered essential to test more than one. Stereoacuity, or the perception of depth based upon the disparate images seen by the two eyes, was selected as the most important binocular mechanism. The perception of the depth of large low contrast contours was also chosen since it is most like the skier's visual task.

Apparatus and Procedure

All depth perception tests were illuminated by 300 watt Macbeth Daylight lamps, providing CIE Illuminant C. Two different tests of stereoacuity were employed. One, the classic Howard-Dolman test consisted of three black metal rods positioned in front of a white background, and behind a rectangular opening which eliminated the top and bottom of the rods from the subject's view. The two outside rods were stationary while the center one could slide on a track front to back. Two lamps, one in front and below the apparatus, the other above and behind, illuminated the sticks. This lighting provided 3.2-3.5 footlamberts (10-12 cd/m^2) between rods and also eliminated shadows on the background. The subject sat in a chair 20 feet from the apparatus which was at eye level.

The subjects' stereoacuity thresholds were determined by the method of constant stimuli, the subject reporting whether the middle rod was closer or farther away. Seven settings of the middle rod were employed; equality of distance, 3 closer and 3 farther in 1/4 inch steps. Five judgments were made at each setting for a total of 35 judgments per session.

The second test of stereoacuity was devised from random-dot stereograms.* The test consisted of 28 cards, each with a stereogram of a plus sign, diamond, circle, or square which appeared either in front of or behind the background. The disparity was always the same, 25 minutes of arc, but the number of dots in the form that were shifted varied from 100% to 50% of the total, in 5% increments. The cards were presented in a Keystone Telebinocular; the luminance of the white portion of the card, when in the telebinocular, was 15 fL (50 cd/m^2). Subjects adjusted the viewing distance of the telebinocular until a practice card was in sharp focus; this setting was noted and used for all subsequent trials.

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* This test was designed and constructed by Dr. Mark Vernoy of Palomar College, CA. We are indebted to him for making it available.

Subjects reported the shape of the figure and its position relative to the surround. The first 8 cards represented all combinations of shape and placement, with 100% of the dots displaced. These were practice trials and subsequent cards were of increasing difficulty. Subjects were allowed a maximum time of 15 seconds per card to make their judgments. The experimenter continued to place cards in the viewer until an error of shape and/or placement occurred on two consecutive cards. The last correct response was then taken as the score.

A special apparatus was constructed for the depth contours experiment. A wooden frame 5'8" long, 3'8" wide, and 2'9" high had a piece of off-white canvas attached to one end. When pulled taut, the canvas would form a smooth, nearly flat surface parallel with the floor. If the material was pushed toward the center, it would form a smooth depression. The ends of the canvas rested on more than 1 ft of wood and therefore were always smooth and flat. The subject stood on a small box at the end of the frame where the material was attached, and viewed the center of the frame through a rectangular hole in a suspended blind. This view included some of the flat surface on both the near and far sides of the depression, excluding the sides of the frame. A canvas flap covered the viewing hole between trials and was raised by the experimenter for judgments by the subject. The contours were illuminated by the Daylight lamps to a level of 9.0 fL ($30\ cd/m^2$).

In the depth contours experiment, subjects estimated the depth of the canvas depression. They were initially shown the shallowest setting, which was called "10", and the deepest, which was referred to as "100". There were 8 evenly spaced settings in between which were not made known to the subjects. The experimenter, following a random number pattern unique to each subject, then made 50 settings, 5 at each of the 10 depths. Subjects made magnitude estimates of the depth of the depression based on their knowledge of a "10" and a "100".

Subjects

The subjects were ten male and four female volunteers of the Naval Submarine Medical Research Laboratory military and civilian staff. Six subjects participated in all three experiments. Four participated in only the depth contours task, while four others participated in only the Howard-Dolman and stereopsis tasks. The latter two tests were always administered together, while the depth contours test was given separately.

Goggles

Four pairs of goggles were used in these experiments: light neutral density, yellow, dark neutral density, and "glacier" type (a dark yellow designed for extremely high light levels). The light and yellow goggles were matched for a transmittance of .78, while the dark and "glacier" goggles both had a transmittance of .09. Subjects who wore glasses were able to fit these goggles over their frames. The spectral transmittances of the various goggles are shown in Fig. 1. The subjects performed all tests under five separate conditions, on five days, four of the times with goggles and once without. The order in which the goggles were worn was counterbalanced across subjects.

The chromaticity coordinates of the goggles are plotted on a CIE chromaticity diagram in Fig. 2. Both neutral densities plot in the center of the diagram close to Illuminant C. The yellow and glacier goggles likewise are of similar chromaticity, the major difference, of course, being one of transmittance, the glacier transmitting a log unit less light.

Results

Stereoacuity

The average results for 10 subjects on the Howard-Dolman test are shown in Fig. 3. The stereoacuity thresholds, taken as the cross-over point for "closer than" and "farther than", and the average standard deviations of the closer and farther judgments are given in Table I, together with the average percent correct judgments for the 10 subjects. The differences among the various goggles are all small and non-significant. Comparison of the pairs matched for luminance (the yellow and light neutral density or the glacier and dark neutral density) shows no superiority of one over the other. The only consistent difference in the table is that performance is poorer for the two darker goggles, the glacier and dark neutral density, than for the other three conditions. This is true of the variability of the stereoacuity thresholds and of the percentage of correct judgments. This is, of course, just a function of the lower luminance level through the darker goggles.

Table I. Measures of depth perception from Howard-Dolman Test of stereoacuity

	No Goggles	Yellow	Light N.D.	Glacier	Dark N.D.
Stereoacuity in arc-seconds					
Limen	0.36	1.08	0.22	0.72	0.45
σ	3.90	3.36	3.70	4.37	4.14
Percentage of correct judgments					
Mean	85.7	88.7	86.0	83.7	82.7
σ	5.9	5.5	10.3	8.1	11.3

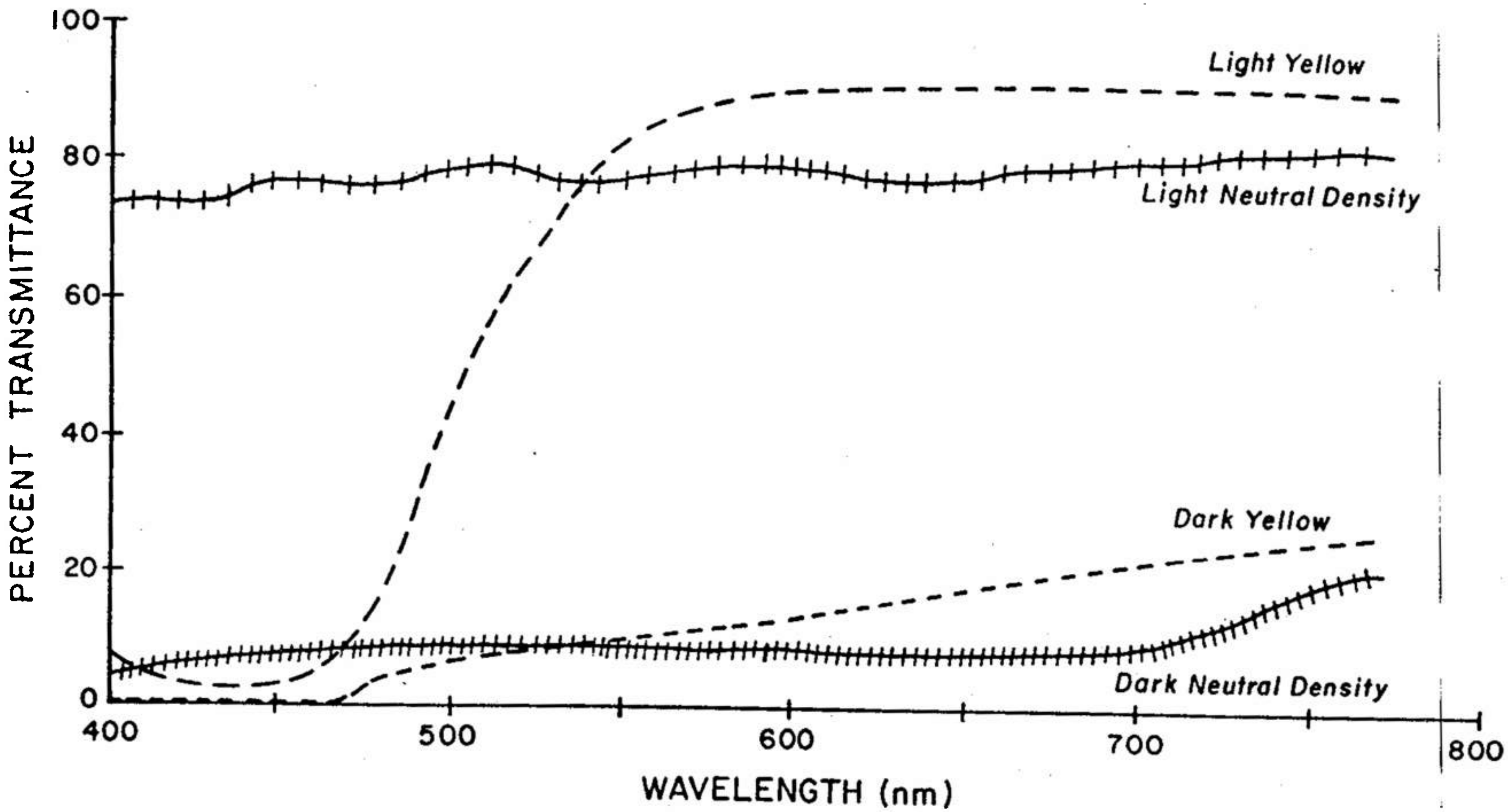

Fig. 1. The spectral transmissions of the various goggles used in the experiments.

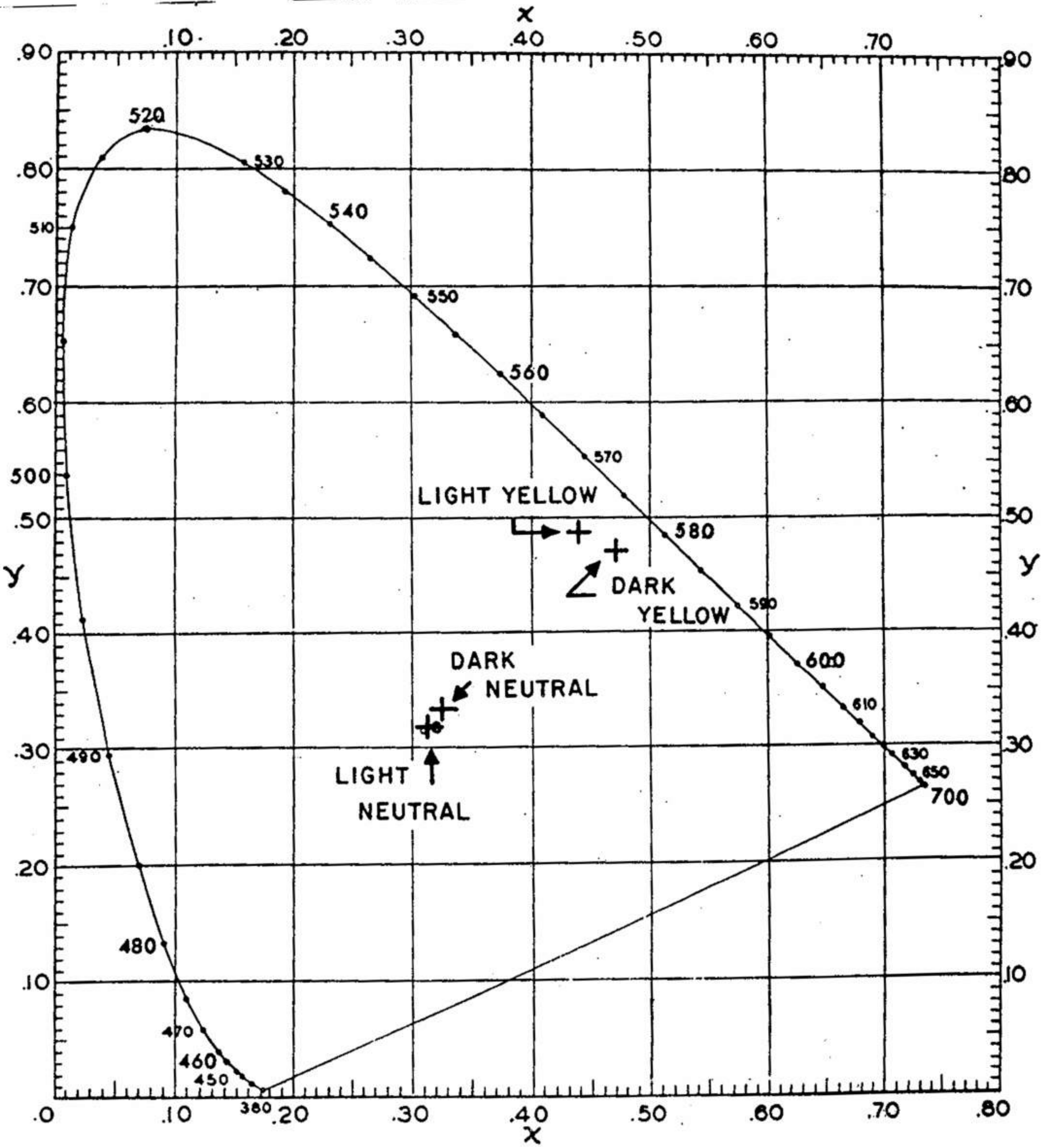

Fig. 2. Diagram showing the CIE chromaticity values of the various goggles used with daylight (Illuminant C).

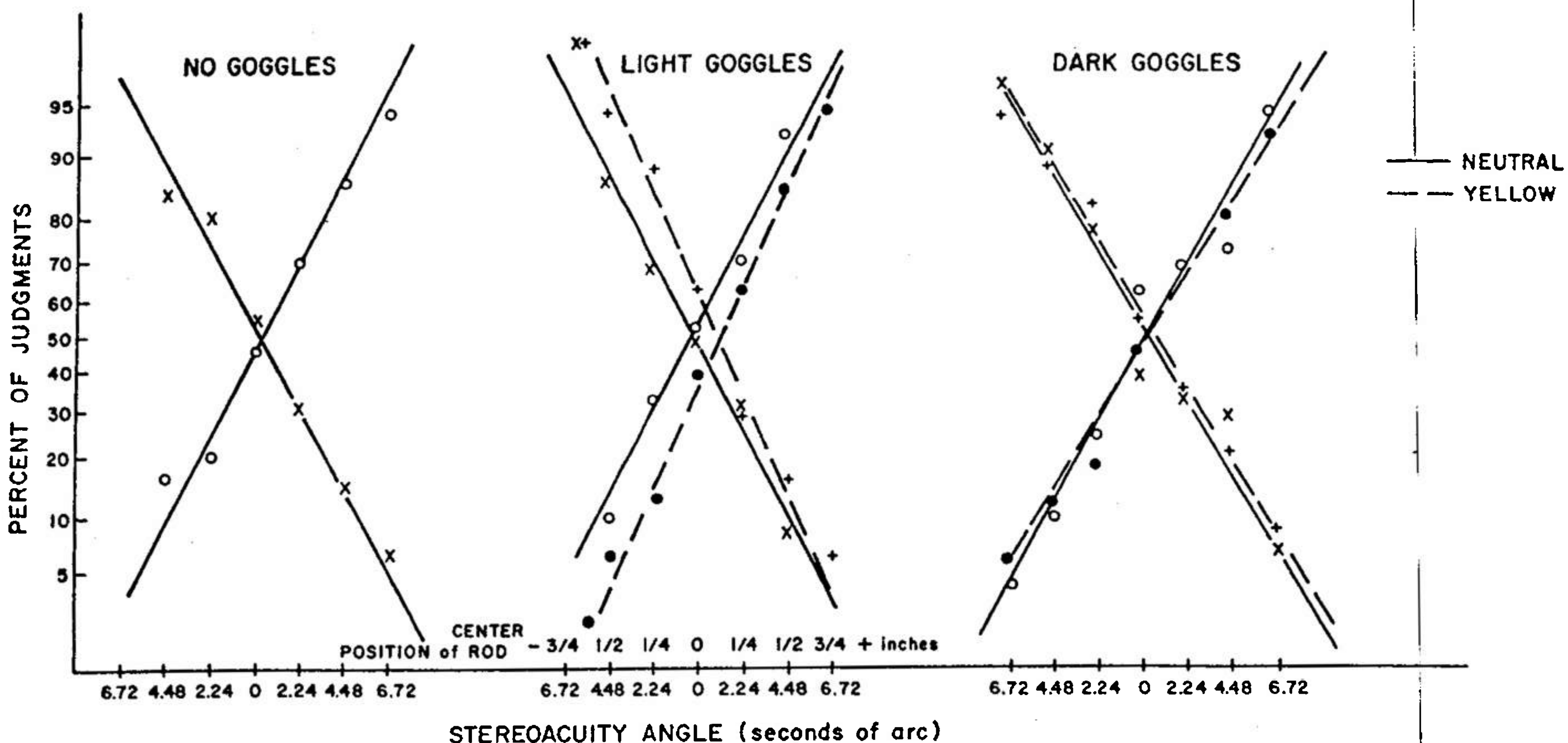

Fig. 3. Cumulative frequency distributions of the percentages of judgments called closer (X) and farther (O) at each setting of the Howard-Dolman rod. Yellow and neutral goggles of the same transmittance are compared. Mean of 10 subjects.

Table II gives the results for the other test of stereacuity, the random-dot stereograms. The stereograms differ in the percentage of dots in the form that are shifted; thus correctly perceiving the form and depth, with a lesser percentage of shifted dots, represents better stereo-acuity. Again there are no differences among the goggles.

Table II. Performance on random-dot stereograms through the various goggles

		No Goggle	Yellow	Light N.D.	Glacier	Dark N.D.
Percentage of dots shifted	Mean	79.5	79.5	78.5	78.5	80.0
	σ	5.99	7.98	7.47	7.47	5.27

Depth Contours

Sample judgments on the depth contours are shown in Fig. 4 for one subject. For this subject, no goggles produced judgments closest to complete accuracy and the dark neutral density yielded the least accurate.

Several statistical analyses were made of the magnitude estimates and an analysis of variance performed on each. The analyses included the exponent in the power function, $\psi = K\phi^n$ (23); a measure of the variability of the estimates for each stimulus $(\sigma/\bar{X})$; and the sum of the squared deviations around the line of perfect fit. Table III gives the results of these analyses.

The slopes of the power functions were all very close to unity, implying excellent agreement between the magnitude estimates and the physical depths. The task was somewhat easier than intended, due probably to the use of the two end-points. Nonetheless, some differences among goggles are evident. Differences among goggles yielded an F ratio of 2.48, for a probability of about .10. Both dark goggles yield poorer performance than the lighter ones, which do not differ significantly from one another, and the dark neutral density is significantly worse than the glacier goggles ($p < .05$).

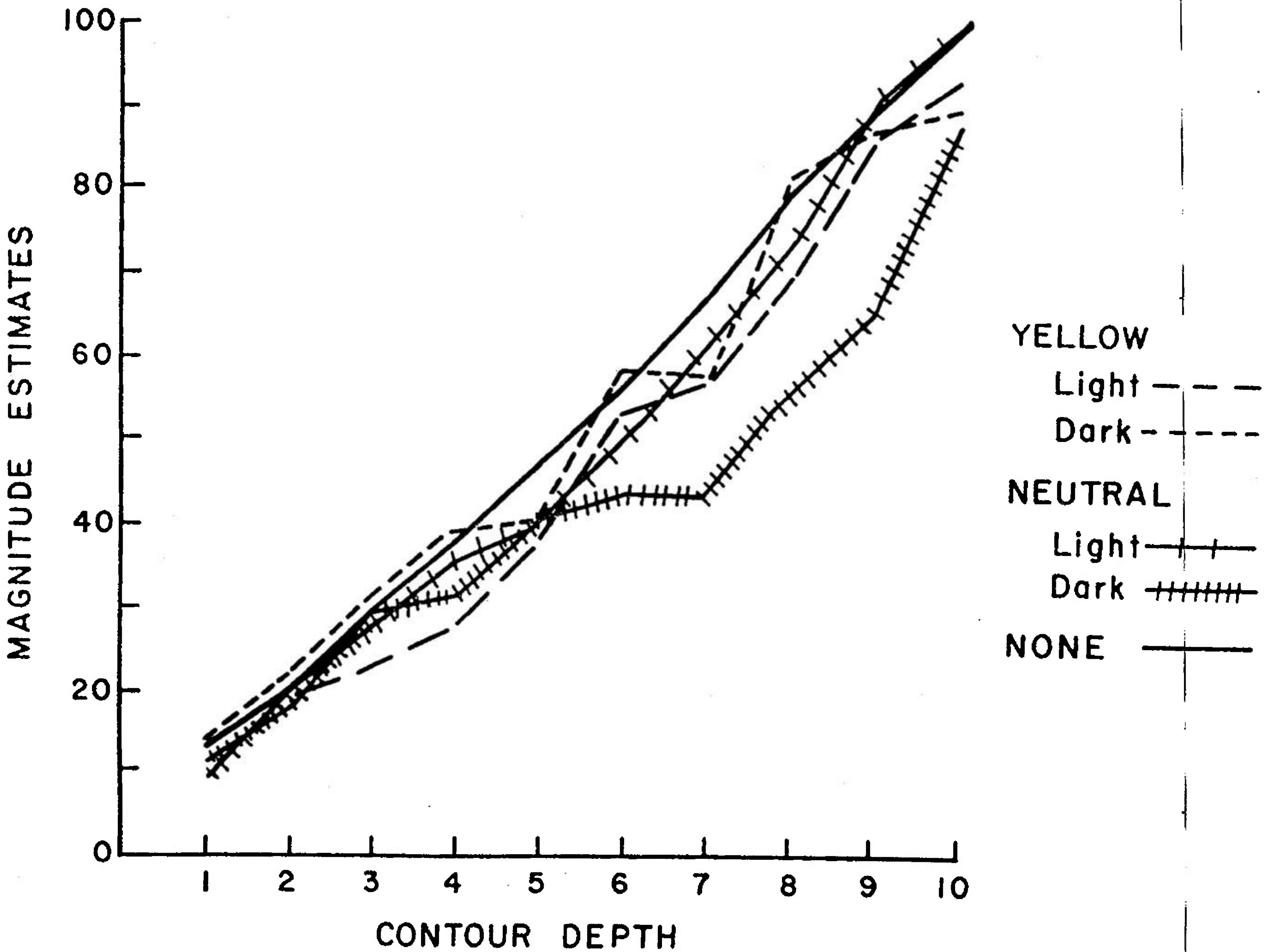

Fig. 4. Magnitude estimates made with various goggles at each of the depth contour settings.

Table III. Analysis of the magnitude estimates through the various goggles

	No Goggle	Yellow	Light N.D.	Glacier	Dark N.D.
Exponent					
Mean	1.03	1.02	1.04	0.96	0.91
σ	.09	.09	.10	.16	.21
Variability of judgments					
Mean	.137	.138	.153	.229	.248
σ	.050	.054	.048	.115	.118
Squared deviation from perfect function					
Mean	562.5	599.9	541.7	1022.7	1593.2
σ	402.2	364.3	371.1	1124.6	1009.9

The analysis of variance of the variability measures ($\sigma/\overline{X}$), showed significant differences among the goggles ($F = 5.80$, df=4,36, $p < .01$). This is due mainly to the fact that the two darker goggles yield significantly more variable judgments than the others. However, the yellow was better than the light N.D. and the glacier better than the dark N.D. at probabilities of .15 and .10, respectively.

The analysis of variance of the squared deviations from perfect judgments also yielded significant differences among goggles ($F = 4.80$, df=4,36, $p < .01$). Again there were no significant differences among the no goggles and the yellow and light neutral density. Both darker goggles produced poorer performance and the dark neutral densities were significantly poorer than the glacier ($p < .01$)

Summary of Depth Experiments

There were no differences among the various goggles when the measure employed was that of stereoacuity, but the yellow goggles did appear to improve the perception of depth contours. This was particularly apparent when the task became more difficult, that is, in the comparison between the two darker goggles. Performance with the yellow, glacier goggle was always better than the dark neutral density, no matter what measure was employed.

EXPERIMENTS ON CONTRAST SENSITIVITY

Background

The perception of contrast is a visual function suggested from practical experience, since it is the visibility of low contrast targets which reputedly is improved by yellow goggles. Furthermore there is now widespread belief that the measurement of contrast sensitivity is an effective and meaningful measure of visual capacity (24). It encompasses both the traditional measurement of acuity and also gives information on the ability to perceive large, low contrast objects. The specific measure of contrast was chosen on the basis of theoretical considerations; this measure was reaction time to spatial frequencies of varying contrast.

There is now a considerable body of evidence (25-27) that mammalian visual systems have two types of neural mechanisms. One of these, the transient system, responds briefly at both stimulus onset and offset and is primarily sensitive to large stimuli (low spatial frequencies). The other, the sustained system, responds continuously during the entire duration of the stimulus and is most sensitive to small stimuli (high spatial frequencies).

These two neural mechanisms have been implicated in differences in human reaction times to varying spatial frequencies. Thus several investigators (28-30) have shown that reaction times to simple sine wave gratings increase with the frequency of the sine wave; this change has been attributed to the differential activity of the transient and sustained systems. Tolhurst (31) has shown that bimodal distributions of reaction times are found for low spatial frequencies, indicative of the transient response, while the data for high spatial frequencies are characterized by unimodal distribution. Harwerth and Levi (32) give evidence that both the transient and sustained systems respond to all spatial frequencies in the middle of the range, with the contrast of the sine wave the determining variable as to which one responds. Finally, Harwerth, Boltz and Smith (33) have used three techniques, previously employed with humans, to infer the activity of transient and sustained systems, on macaques and have obtained data comparable to that from humans. Since some of the original data on sustained and transient systems were obtained from single cell electrodes in macaque visual system, the theorizing has come full circle.

There are two important implications of this theorizing for yellow goggles. First, if there is overlap between the functions of the transient/sustained systems and the achromatic/opponent-color systems, yellow goggles should show advantages for specific contrasts of specific sized targets (spatial frequencies). Second, the reaction time paradigm should be a sensitive indicator of this possibility.

Consequently two experiments were conducted in which reaction times were measured for various grating targets. The first employed square waves, .5 cpd to 10 cpd in size, of varying contrast. In the second experiment four contrasts of both square and sine waves of .5 and 2 cpd were used with both a lighted and an unlighted surround.

Reaction Times to Spatial Frequencies of Varying Contrast: Exp. I

Apparatus and Procedure

Square wave gratings were produced photographically, pasted on cards, and presented to subjects in a three-channel tachistoscope. Four different spatial frequencies (.5, 2, 5, and 10 cpd) were employed. Three to four contrasts, varying from .60 to .03, were available at each frequency, yielding 14 different cards. Contrasts were measured with a Spectra Pritchard Photometer and calculated from the formula

$$C = \frac{L_L - L_D}{L_L + L_D}$$

where L_L is the luminance of the brighter stripe, and

L_D is the luminance of the darker stripe.

The gratings, 6.5 cm square, subtended 3 degrees on a side at the observing distance of 125 cm. In addition there were three blank cards with a gray square matched in average reflectance to the gratings.

Gratings and blank cards were presented for 100 msec in one channel of the tachistoscope. When they were not illuminated, a second channel of the same luminance, with a single fixation point, was substituted so that the subject looked continually at a white background of 12 fL (40 cd/m^2). Goggles were the same as employed in the experiments on depth perception. Thus there were three overall luminance levels: no goggles or 12 fL, the light yellow and light neutral densities, at an effective level of 9.4 fL (12 x .78) and the dark yellow "glacier" and dark neutral densities at 1.1 fL (12 x .09).

All 17 cards were presented, in random order, seven times each in a single session. Five sessions, one for each goggle, were run on separate days, with the order counterbalanced across subjects. Complete data were collected on ten subjects.

Subjects were told that they would see stripes of various size; some of these would be easy to see, some very difficult, and sometimes there would be no stripes at all. Their task was to press a button, as quickly as possible, as soon as they saw stripes, but not to respond unless they saw stripes. A practice session, with all 17 cards, was given first.

Results

Median reaction times were calculated for each subject for each condition and averaged over the 10 subjects. These data are plotted in Fig. 5 as a function of contrast. Reaction times increase with decreasing contrast and also are longer for the dark pairs of goggles than for the light. The comparison between yellow and neutral density goggles of equal transmission shows generally faster reaction times for the yellow. The only reversals occur for the higher spatial frequencies, most notably 10 cpd for which there appears to be no difference.

There are no overall significant differences between yellow and neutral goggles, by an analysis of variance, since the reaction times are variable and not all subjects show an advantage for yellow under the same conditions. Nonetheless, the majority of the individuals show faster reaction times for yellow. There are 23 possible comparisons (each contrast at each spatial frequency) for which one can calculate the percentage of the 10 subjects that show an advantage for yellow. The null hypothesis, that there is no difference between yellow and neutral goggles, would predict 50% of the subjects should show an advantage for yellow. The actual average percent of 59.3 ± 13.5 is significantly different than 50% ($p < .01$); furthermore there were specific contrasts of specific spatial frequencies for which 70 to 90% of the subjects gave faster reaction times for yellow; these were generally the medium and low contrasts of 2 and 5 cpd gratings. None of these high percentages occurred for the .5 cpd grating.

Reaction times with no goggles are compared with those using yellow goggles in Fig. 6. The curves are very similar, with no strong advantage displayed for either condition. The exception at 10 cpd, where yellow goggles are inferior to no goggles, is probably a manifestation of the fact that acuity increases with luminance level. The fact that yellow at a lower luminance level is as good as no goggles, for the larger targets, is another indication of their usefulness.

The first experiment on reaction times to spatial frequencies indicates that there are certain conditions under which yellow goggles are effective. These conditions include lower spatial frequency targets at lower contrasts and specifically exclude the higher spatial frequencies. Since the latter are, of course, acuity measures, this is in agreement with the literature that there is no advantage to the use of yellow goggles for acuity.

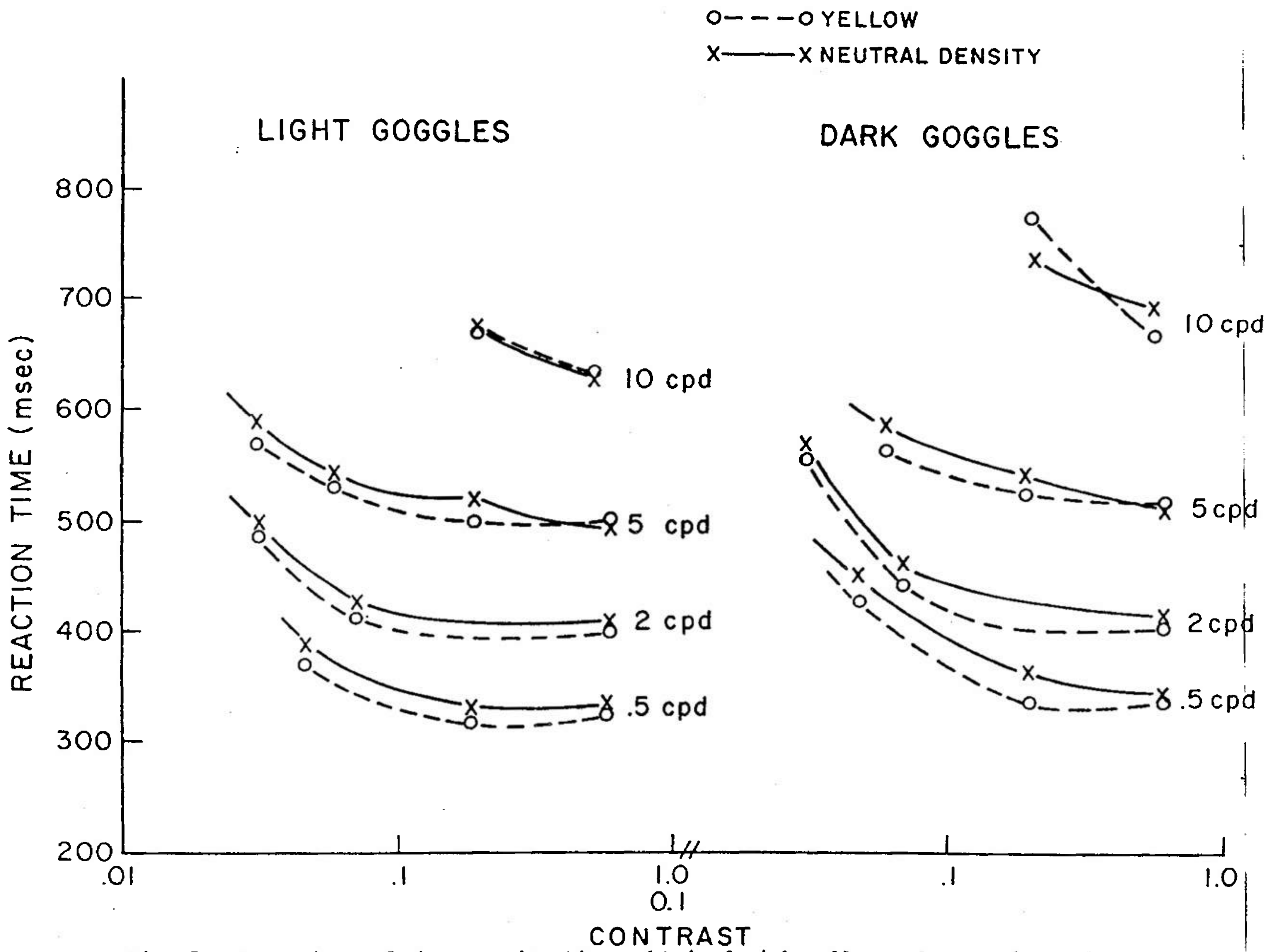

Fig. 5. Comparison of the reaction times obtained with yellow and neutral goggles at various spatial frequencies. Data are the means of the median responses of 10 subjects. The curves for .5 cpd are on a true scale but all other curves have been successively shifted up by 100 msec for ease of viewing.

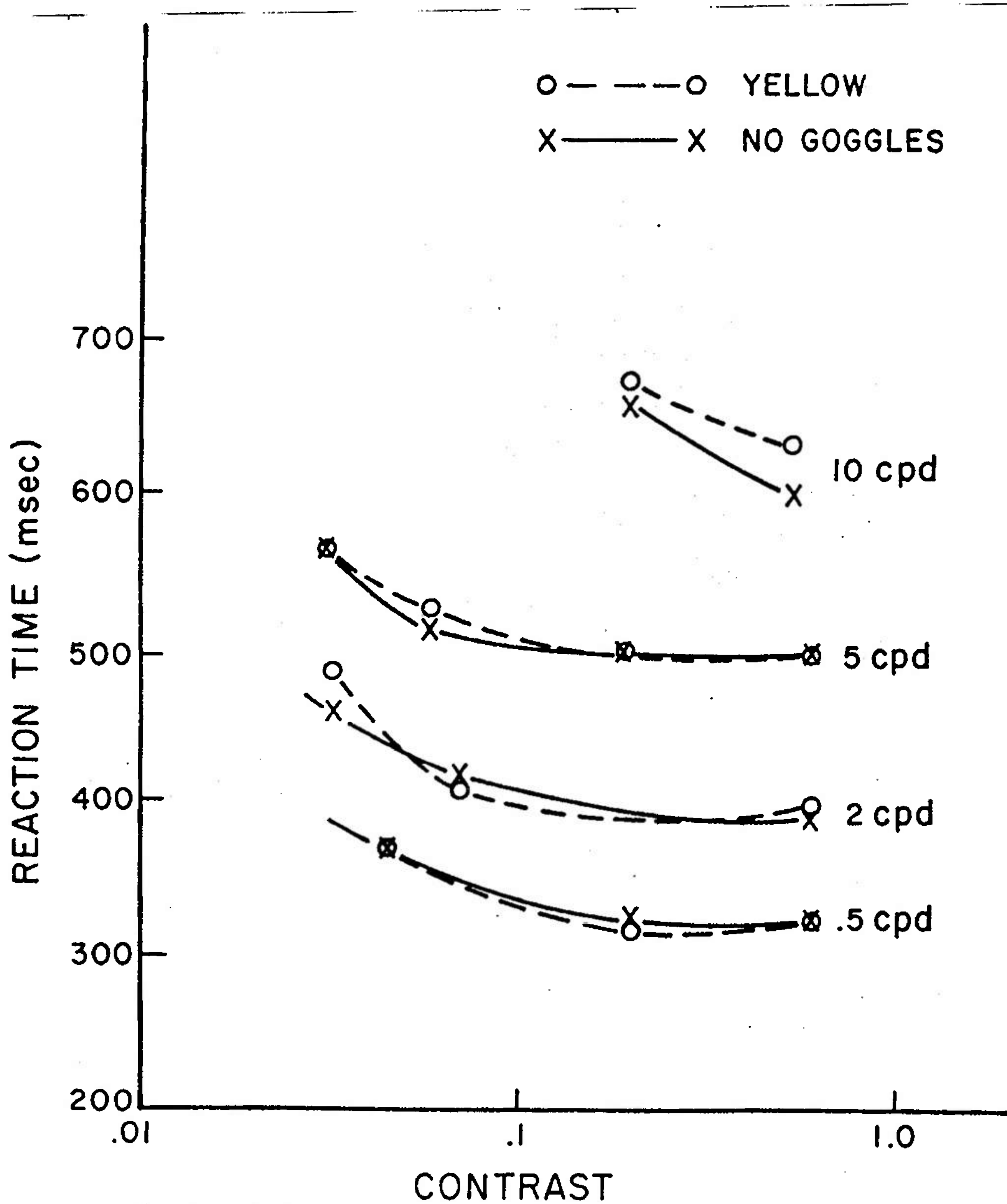

Fig. 6. Comparison of the reaction times obtained with light yellow goggles to those with no goggles. All other details are the same as Fig. 5.

The results from Experiment I gave general support to the suggestion that there would be specific contrasts of specific spatial frequencies for which yellow goggles would prove superior to neutral goggles. Experiment II was designed to test predictions generated by these data in conjunction with the physiological theories of color vision.

The data of Harwerth and Levi (32) indicate that the sustained channels respond to all contrasts of high spatial frequencies (10 cpd and higher) and to low contrasts of many spatial frequencies in the middle of the range of human sensitivity (1 to 8 cpd). The transient channels on the other hand respond to all low spatial frequencies (.5 cpd or less) and to high contrasts in the middle of the range. Therefore two specific spatial frequencies were chosen for more extensive investigations, .5 and 2 cpd. The higher spatial frequencies were eliminated from consideration since both previous work (1) and the data from Exp. I show that for them yellow goggles offer no advantage. A wide range of contrasts were used for each spatial frequency.

In order to show an advantage for yellow goggles, theoretically, one must deal with the output of the opponent-color system. It is, however, necessary to suppress the contribution of the achromatic system, since in many situations both may operate. Indeed, Nissen and Pokorny (20) suggest that reaction times will be determined by the fastest channel, which will normally be the achromatic channel if both are allowed to respond. Therefore several stimulus parameters were chosen to enhance the activity of the opponent system relative to that of the achromatic. The grids were presented against a white surround and were of long duration, both conditions having been reported to emphasize opponent contributions (9). The long duration had the additional advantage of reportedly differentiating between transient and sustained response by yielding bimodal and unimodal distributions of reaction times (31,33). Finally, grids were constructed of both square and sine waves, since one report in the literature showed an advantage for square waves but not for sine waves (34).

Apparatus and Procedure

Gratings* for this experiment were produced on an oscilloscope in order to obtain better control of contrast than was available in Exp. I. Both sine and square waves of .5 cpd and 2 cpd were presented for 500 msec. Control of both duration and spatial frequency was maintained by

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* The authors wish to thank D. Douglas Wray for the design and fabrication of the system used to present spatial frequencies.

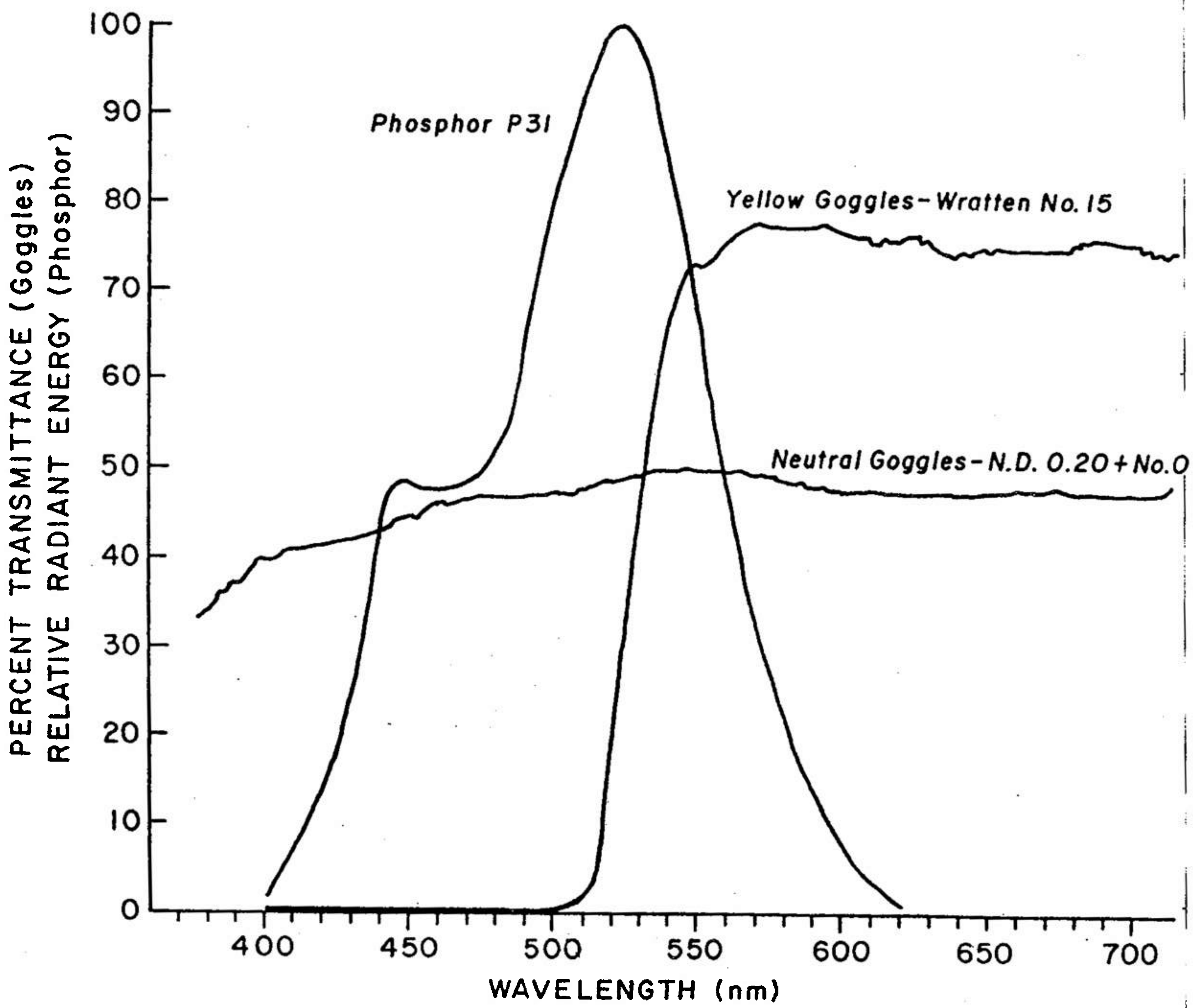

Fig. 7. Spectral transmittance of the yellow and neutral goggles and the relative spectral radiant energy distribution of the P31 oscilloscope phosphor.

the use of several function generators. The scope had a P31 phosphor; this appears green but actually had significant energy through the region from 400 to 600 nm. The spectral energy distribution is shown in Fig. 7.

Contrast was varied in four equal dB steps for each condition by means of a decade attenuator. The four dB settings produced approximate contrasts of .50, .15, .05, and .015. The actual contrasts were measured with a Spectra Pritchard Photometer and varied slightly with the type of grid and the lighting condition. The mean luminance for all contrasts was 2 fL (6.7 cd/m^2).

The gratings were viewed through a hole in a white hemisphere; the diameter of the hole was 10^o at the viewing distance of 71.5 cm. The hemisphere was lighted to a level of 20 fL (67 cd/m^2) by two Macbeth daylight lamps for one condition and left unlighted for the other.

Only two pairs of goggles were employed, yellow and a neutral formed out of Wratten filters. The neutral was equated in luminance transmittance to the yellow; for the spectral energy distribution of the CRT, the luminance transmittance of the yellow (Wratten #15) was .47 and the neutral, .49. The chromaticity coordinates of the yellow were $x = .333$, $y - .653$ and of the neutral $x = .203$, $y = .403$. Both sets of coordinates indicate a greener cast than the goggles of Exp. I, due, of course, to the phosphor on the oscilloscope. The transmittances of the goggles are also shown in Fig. 7. *

The four contrasts for each of the four conditions (sine and square waves of .5 and 2 cpd) plus four trials with no gratings were presented in random order; these 20 trials were repeated five times in a single session. Two sessions were run for each condition, yielding 10 reaction times per subject for each contrast. Both yellow and neutral density goggles were employed with both the lighted and unlighted surrounds; these eight experimental sessions were counterbalanced across subjects. Four subjects were employed.

The subjects were again instructed to respond as quickly as possible as soon as they saw stripes, but not to respond to blank stimuli. They were given a ready signal a few seconds prior to the flash and were told to look at the hemisphere between trials.

Results

The reaction times obtained with neutral goggles are presented first to allow comparison with results from the literature for achromatic stimuli. Figures 8 and 9 show the mean reaction times for the four subjects plotted as a function of contrast for each spatial frequency.

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* The authors are grateful to Kevin Laxar for making available this set of goggles and the measurements of their CIE chromaticity values.

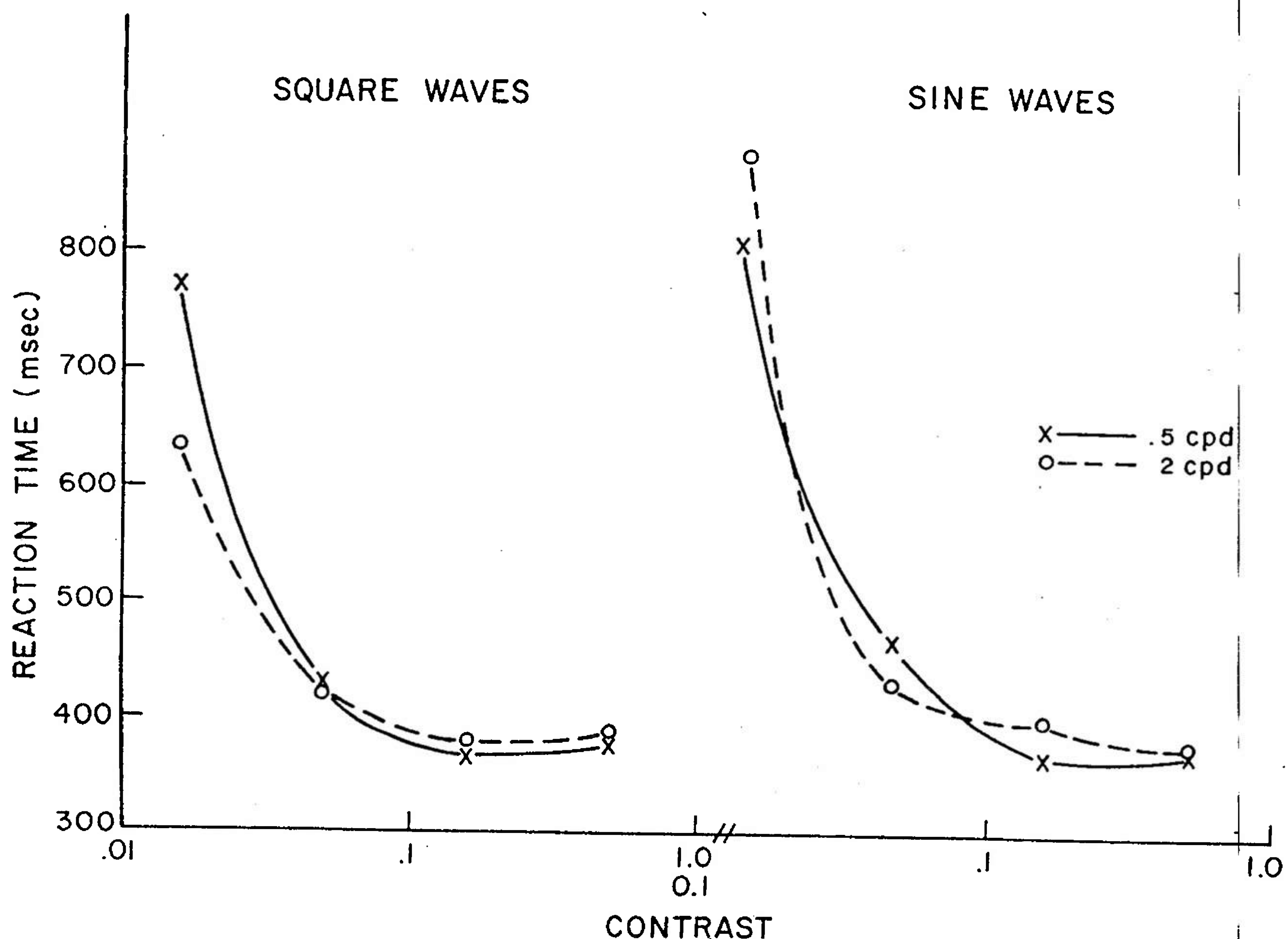

Fig. 8. Reaction times for neutral density goggles used with an unlighted surround. Data are the means of the median responses for four subjects.

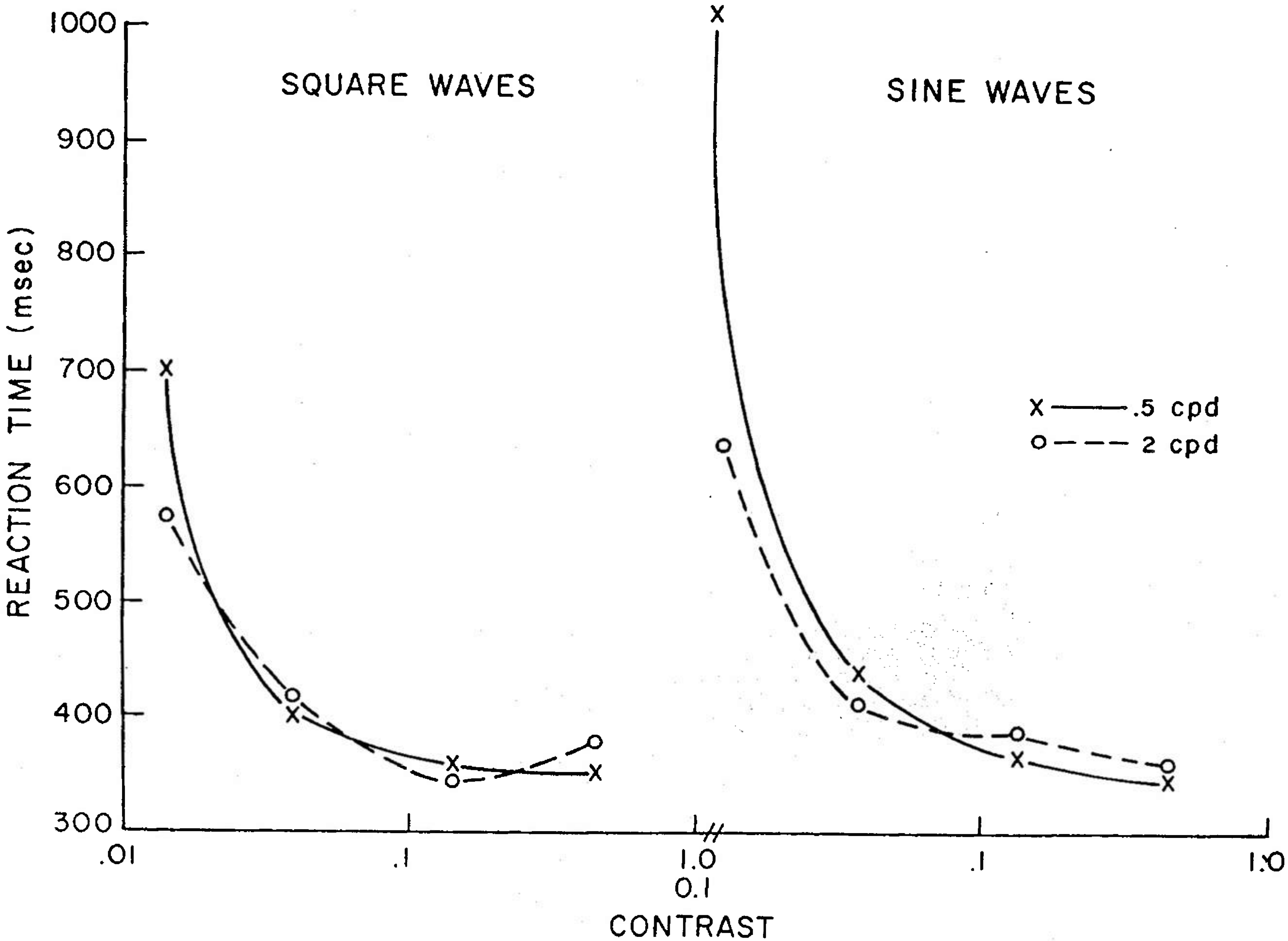

Fig. 9. Reaction times for the neutral goggles used with a white lighted surround. Same subjects as Fig. 8.

Reaction times decrease with increasing contrast, reaching an asymptote at the higher contrasts. There is some indication of a break in the curves for 2 cpd. At the higher contrast, reaction times to .5 cpd are faster than at 2 cpd, but the two curves reverse at lower contrasts so that here times are generally faster for 2 cpd. All of these features are found in the original report of Harwerth and Levi (32). In addition, square waves yield somewhat faster reaction times than sine waves, a fact which can be predicted from Fourier analysis. On the other hand, the differences between lighted and unlighted surrounds are minimal.

Figures 10 - 13 are comparisons of mean reaction times, as a function of contrast, for the yellow and neutral goggles. The curves for the yellow goggles are similar in most respects to those obtained with the neutral goggles. Indeed, with a .5 cpd grating the mean curves are almost identical. On the other hand, the mean reaction times to 2 cpd were almost always faster for the yellow goggles than for the neutral.

Analysis of the individual data, shown in Table IV, yields 64 possible comparisons (4 subjects x 4 contrasts x 4 conditions) between yellow and neutral goggles for each grating. For the .5 cpd grating 65.6% of these favored the yellow and for the 2 cpd, 76.6% of the possible comparisons showed faster reaction times for yellow. These are significantly greater than chance at better than .05 and .01 levels, respectively. In addition, for the 2 cpd target, there was a steady increase in the percentages with decreasing contrast; at the lowest contrast, 87.5% of 16 possible comparisons showed that yellow was better.

Table IV. Percentage of times reaction times with yellow were better than with neutral goggles

Contrast	N	.5 cpd	2 cpd
.50	16	75.0	56.2
.15	16	50.0	81.2
.05	16	68.8	81.2
.015	16	68.8	87.5
Overall	64	65.6	76.6

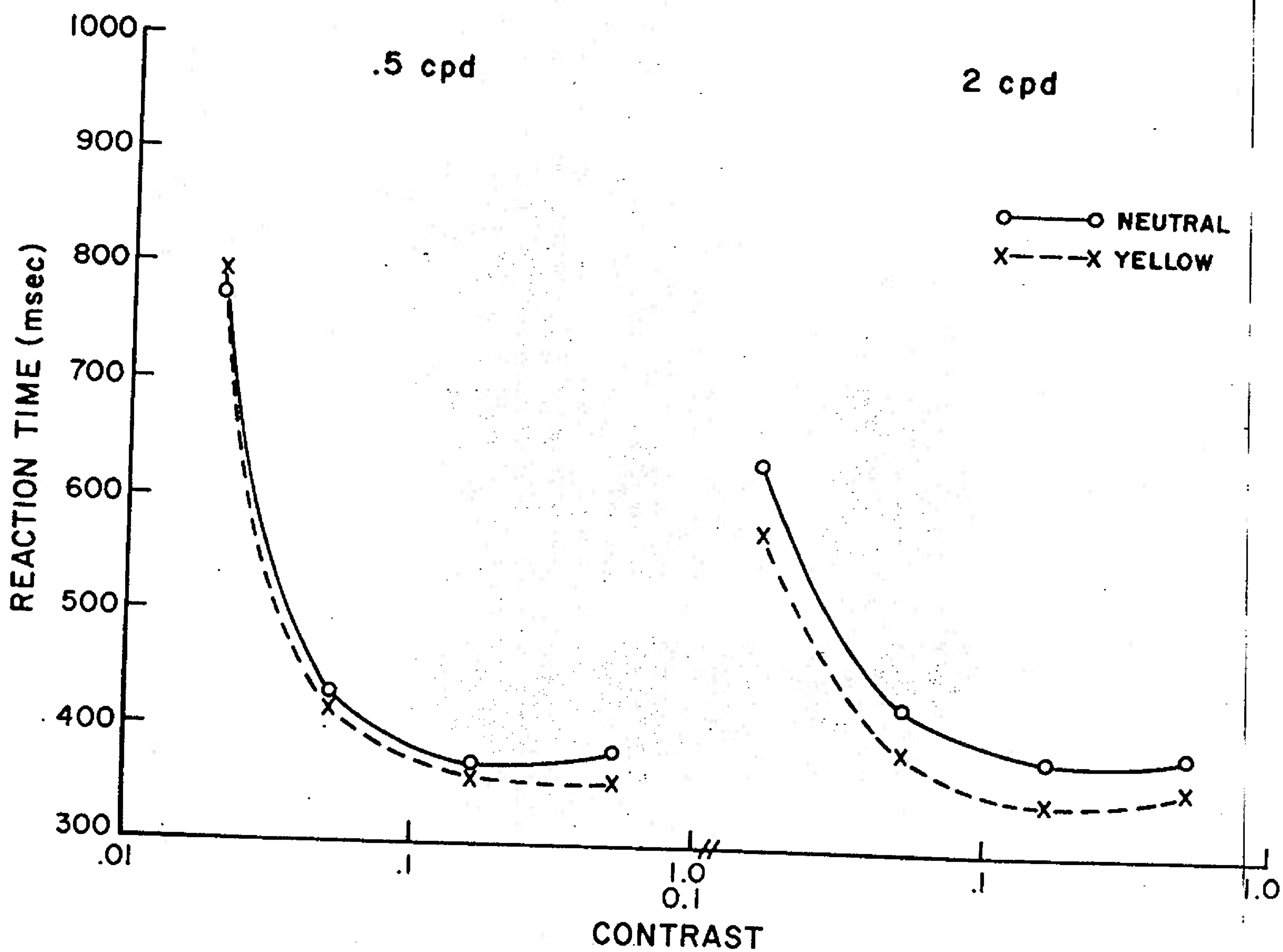

Fig. 10. Comparison of the reaction times obtained with yellow and neutral density goggles for square waves presented against a dark surround.

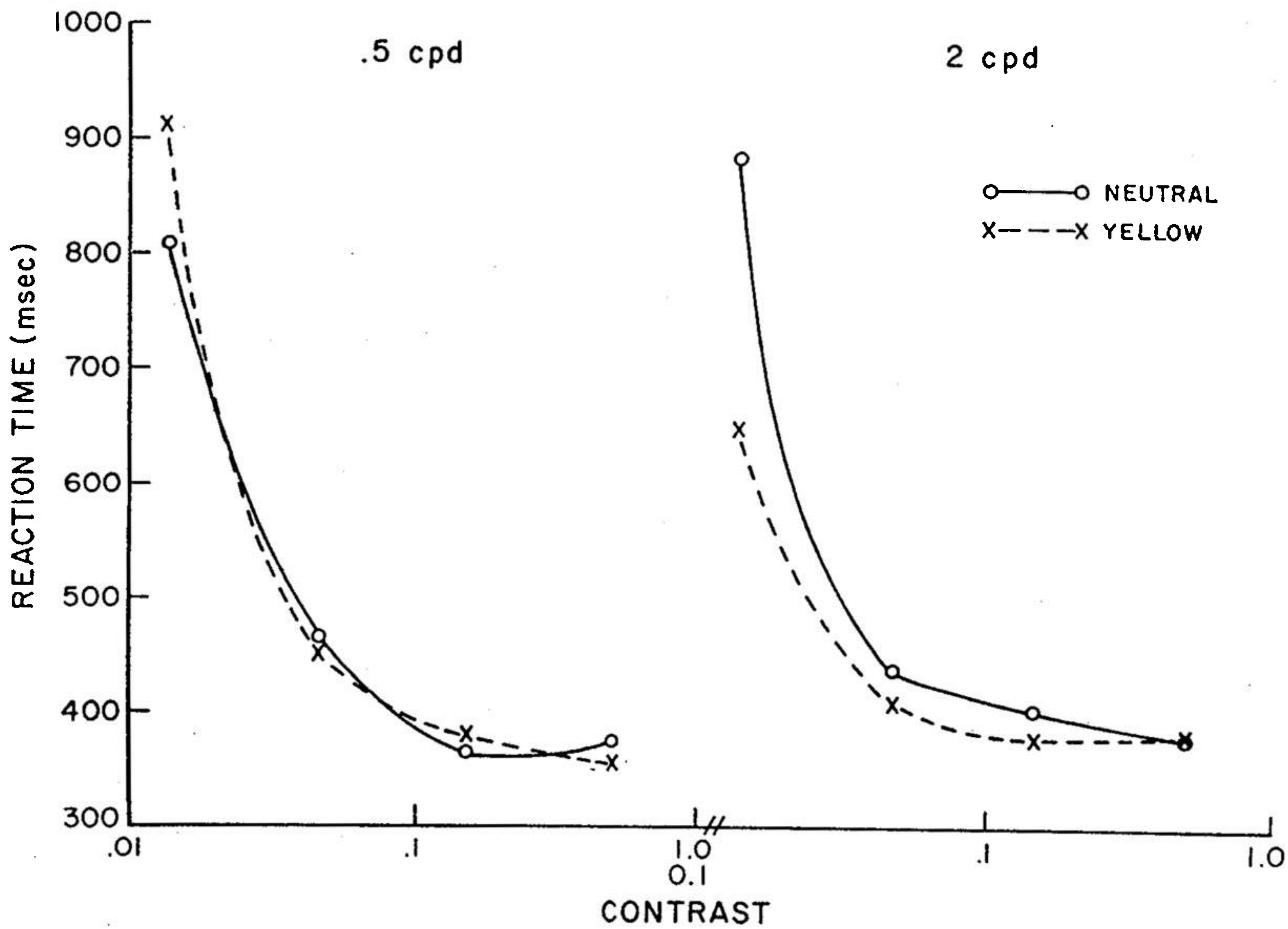

Fig. 11. Comparison of the reaction times obtained with yellow and neutral density goggies for sine waves against a dark surround.

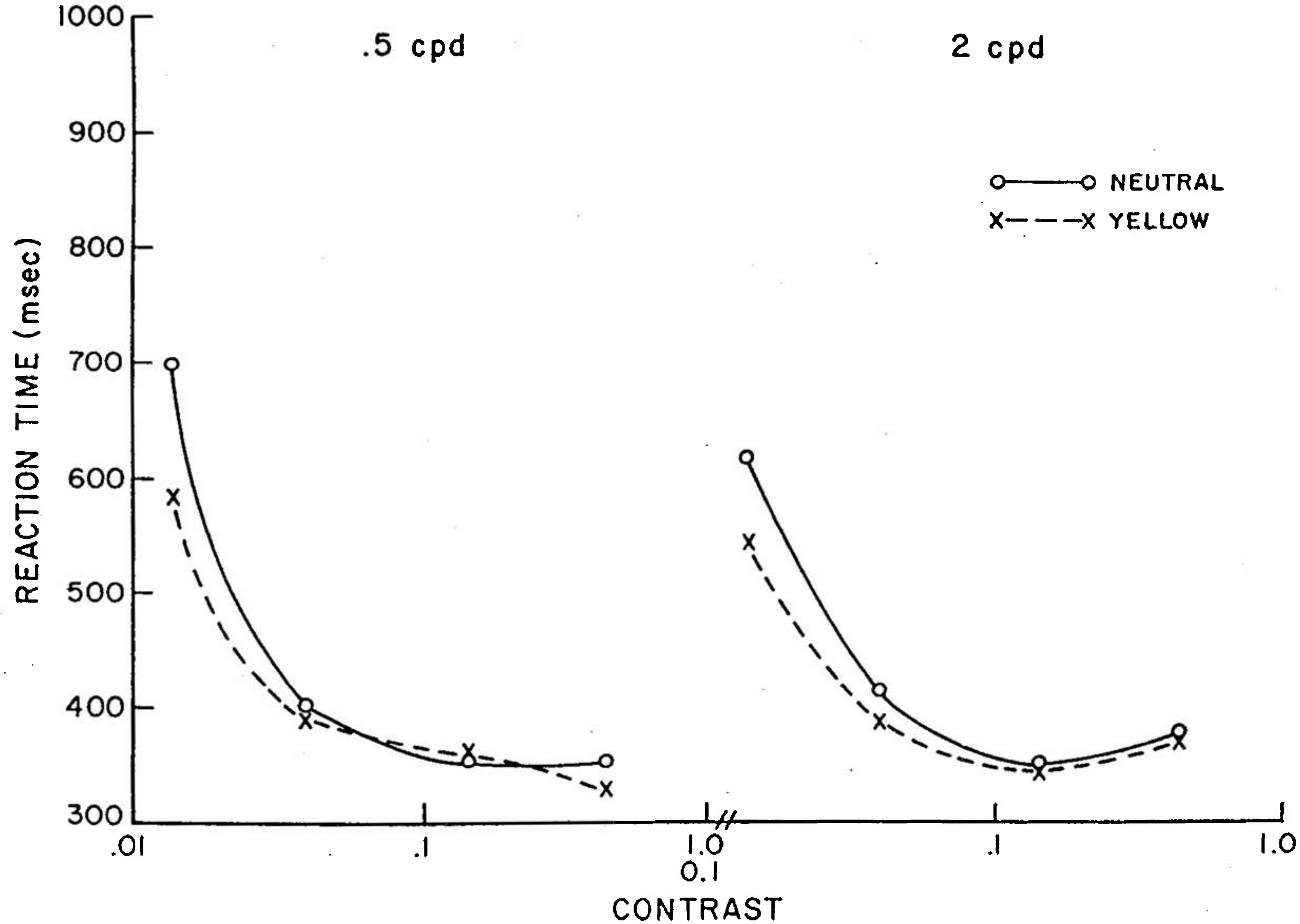

Fig. 12. Comparison of the reaction times obtained with yellow and neutral density goggles for square waves against a lighted surround.

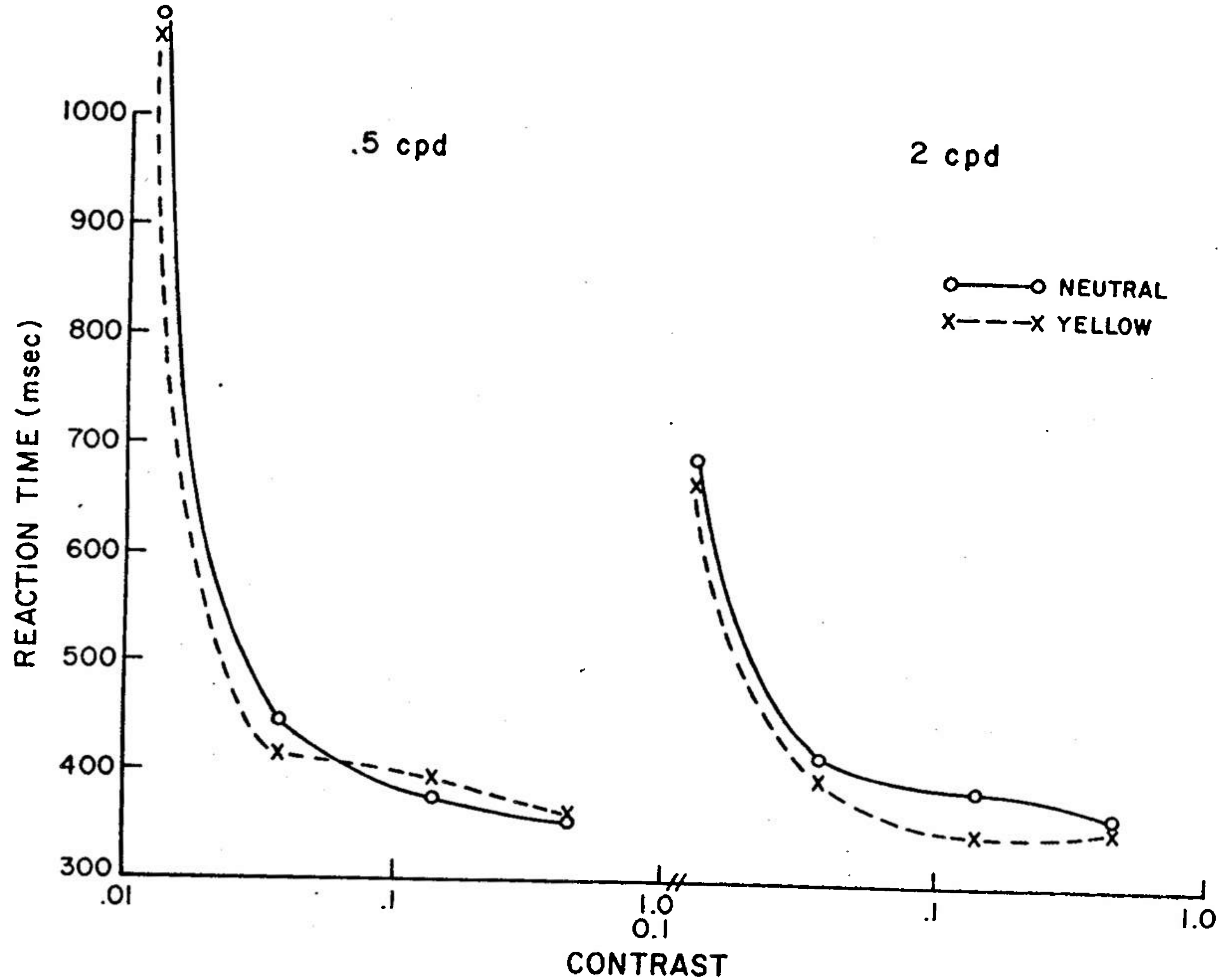

Fig. 13. Comparison of the reaction times obtained with yellow and neutral density goggles for sine waves against a lighted surround.

Analysis of Distributions of Reaction Time

A common method of inferring the activity of the transient or sustained system is to determine the distributions of individual reaction times, since the transient neurons fire at both onsets and offsets while the sustained neurons respond continuously.

In order to investigate the distributions of reaction times, each individual reaction time was converted to a Z score*($RT-\bar{X}/\sigma$ where the mean and sigma were determined for each condition within a given session). These Z scores were plotted in a frequency distribution showing the percentage of time Z scores of different levels were obtained. Figures 14 and 15 show these distributions for the neutral goggles for the two extremes of contrast, the highest and the lowest. Distributions for sine waves and square waves have been combined since there were no differences evident between them, nor should there be any theoretically.

There are two major points to be noted. When the distributions of the .5 cpd are compared with that of 2 cpd, the latter yield higher peaks and are more nearly unimodal than the former. Second, when the distributions from the high contrast targets are compared with those from the low, the low contrast distributions are unimodal and the high contrasts are more bimodal. These data then are in complete agreement with those of Tolhurst (31) and Harwerth et al (33): the sustained channels responding to higher spatial frequencies and to low contrasts of mid-range frequencies are reported to yield unimodal distributions.

Since these analyses of the reaction times from the neutral goggles agree well with the literature and the theory, we conclude we have achieved conditions for which differences between sustained and transient channels are demonstrated. The tests of the effectiveness of the yellow goggles will look for differences between sustained and transient channels. Thus, if the opponent-color system is the same as the sustained system, evidence for effects of yellow goggles should be found in the data for low contrasts of 2 cpd. Specifically, if the use of yellow reduces the opponent inhibition, changes should be apparent in the frequency distribution.

The frequency distributions for reaction times with yellow goggles (Figs. 16-17), do follow this prediction. The peaked unimodal distribution found with neutral goggles for the low contrast of 2 cpd is not

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* Z scores were used instead of the absolute reaction times since individual differences in speed of responding were too great to combine.

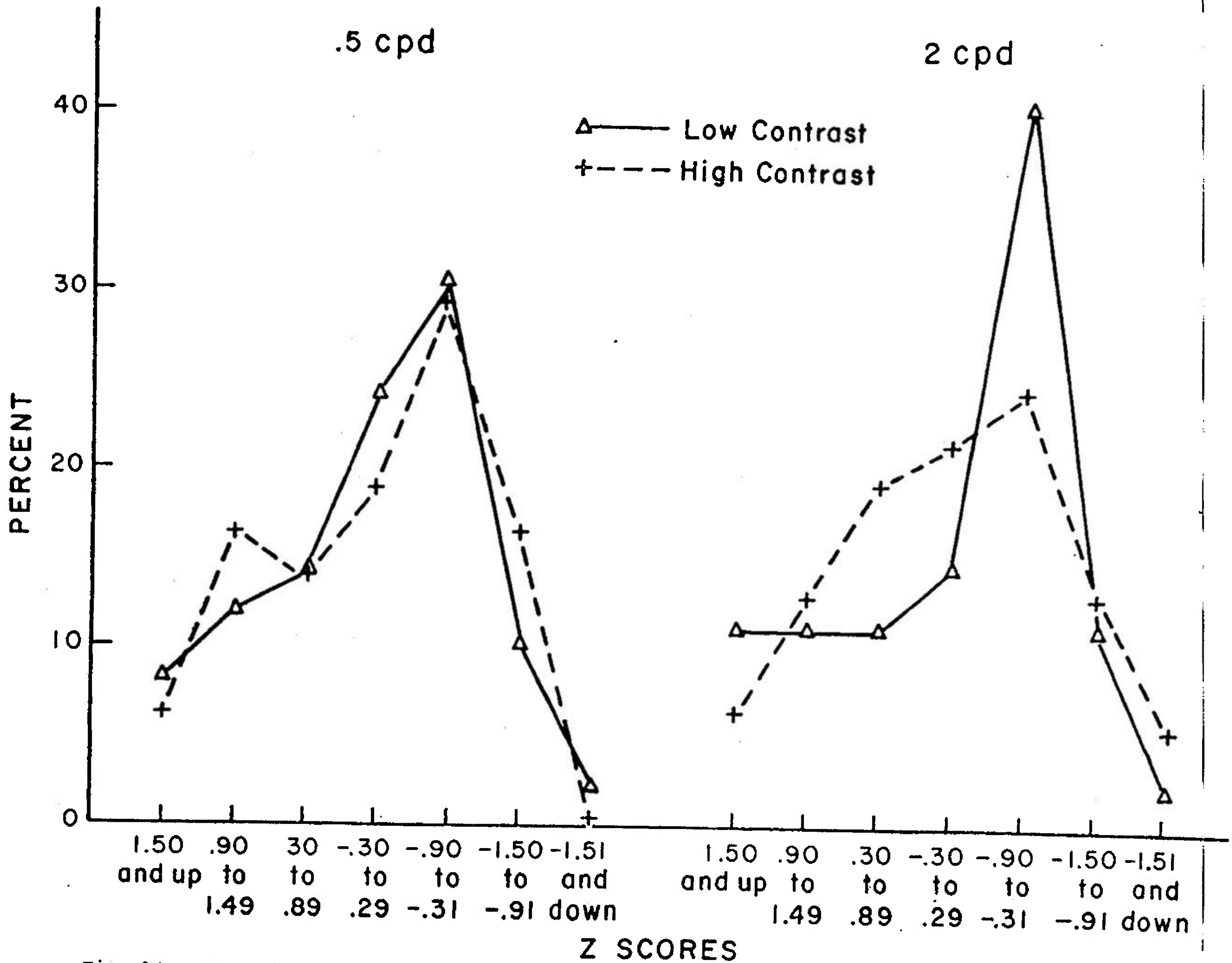

Fig. 14. Comparison for the high (.50) and low contrast (.015) gratings of the distributions of individual reaction times obtained with the neutral goggles and the unlighted surround. Details are given in the text.

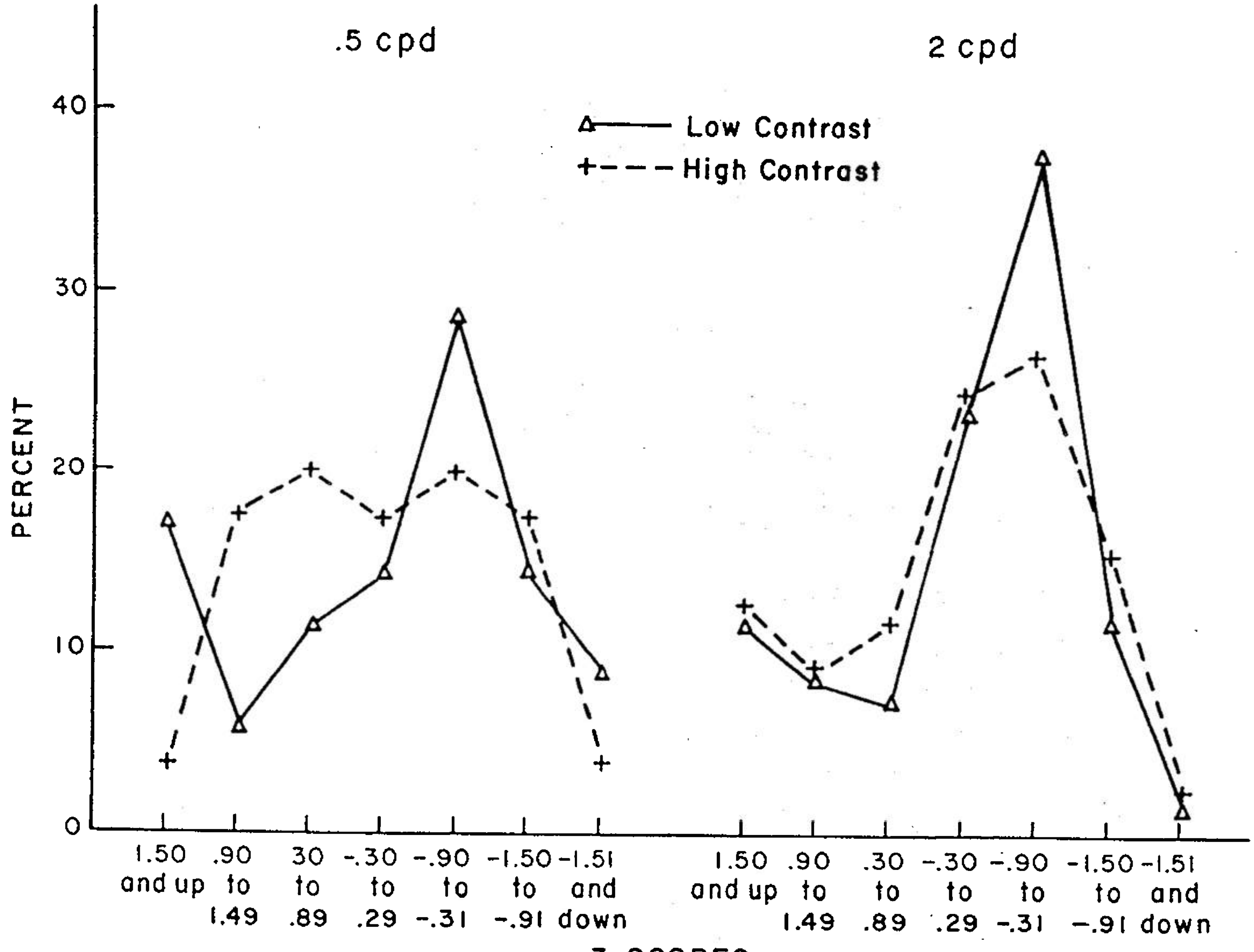

Fig. 15. Comparison for the high and low contrast gratings of the distributions of individual reaction times obtained with the neutral goggles and the lighted surround. Details are given in the text.

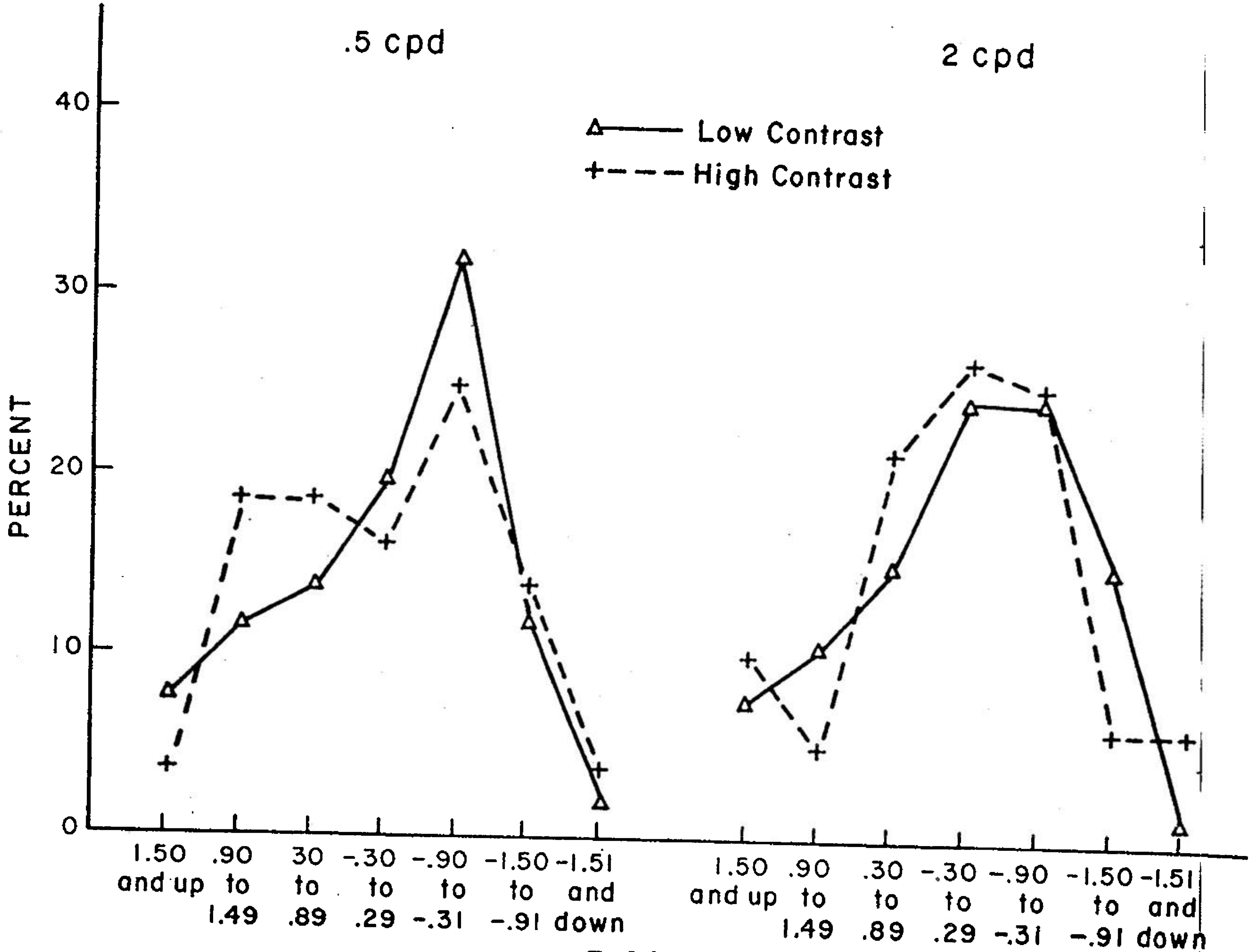

Fig. 16. Comparison for the high and low contrast gratings of the distributions of individual reaction times obtained with the yellow goggles and the unlighted surround. Details are given in the text.

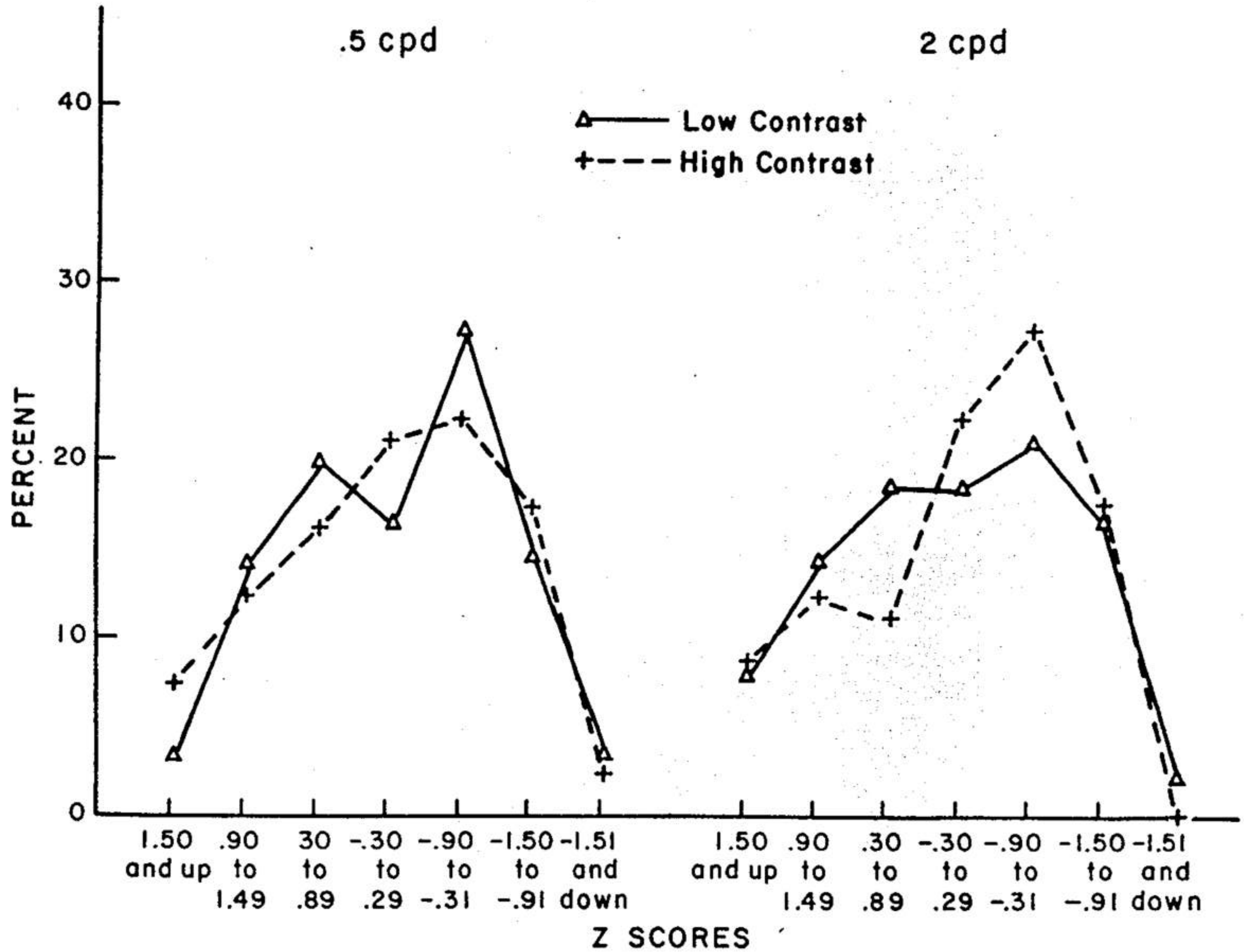

Fig. 17. Comparison for the high and low contrast gratings of the distributions of individual reaction times obtained with the yellow goggles and the lighted surround. Details are given in the text.

found in the data for the yellow goggles. Rather the distributions are flatter and more bimodal.

A reasonable explanation, within the context of the chromatic/achromatic theory lies in the dual response of the opponent mechanism to luminance and hue. Many authors agree that, while the achromatic system responds only to differences in intensity and ignores differences in wavelength, the chromatic system responds to changes in both wavelength and intensity. Evidence comes from both electrophysiology (26, 34) and psychophysics (7,20,35) and shows that the response to wavelength is slower than that to intensity. The peaked, unimodal distribution with neutral goggles could then represent the chromatic channels' responses to luminance differences. With the yellow goggles enhancing the opponent output, the frequency distribution shows a relative shift toward the slower opponent response. This explanation assumes we have effectively eliminated the contribution of the transient system from contention by the use of the low contrast at 2 cpd and by the white surround. Indeed the differences between neutral and yellow is most apparent in the data for the lighted surround, the condition chosen to enhance the sustained contribution.

Summary of Experiments on Contrast Sensitivity

Faster reaction times to many spatial frequencies were obtained with yellow goggles. The spatial frequencies for which yellow was most effective were in the middle of the range, around 2 cpd, near the peak of the contrast sensitivity function for human vision. Low contrasts showed the biggest advantage. Differences between goggles were considerably less at lower spatial frequencies (.5 cpd) and did not occur at 10 cpd.

DISCUSSION

In this series of experiments, a number of visual functions were identified which were improved by the use of yellow goggles, while other functions showed no difference between yellow and neutral goggles matched for luminance. Three issues raised by these results will be discussed: (1) the relation to previous attempts to explain the popularity of yellow goggles; (2) the implications of the data for the theory which led to these experiments; and (3) the practical applications of the wearer of yellow goggles.

Relation to Previous Work

It was pointed out earlier that the many previous attempts made to test yellow goggles had yielded negative results, but that almost all of these had employed visual acuity as the measure (1,22). These data are in complete agreement with previous results: there were no differences between yellow and neutral at the higher spatial frequencies. Sensitivity to high spatial frequencies is, of course, a measure of acuity.

However, there have been recently a few attempts to measure other functions. Richards (36) measured contrast sensitivity for frequencies from .5 to 40 cpd for 11 different colored filters. He reports no differences among filters for sine wave gratings but improvement by yellow filters of detection for gratings less than 2 cpd for square wave targets.

Similarly, Everson and Levene (37) measured contrast sensitivity for sine and square wave gratings through several different colored filters at different luminance levels. They report enhanced sensitivity with yellow filters for gratings in the range of 1 to 5 cpd at a luminance level of about 30 ftL. The improved sensitivity occurred for both square and sine waves but disappeared at very bright luminance levels of about 2500 ftL.

These results are comparable to ours in that spatial frequencies in the center of the range show the improvement. Neither Richards nor Everson and Levene related their data to the achromatic/chromatic model of the visual system employed here. Yet it may be that the differences between the studies can be explained by the model. Field size, luminance level, and the existence of a bright surround can be expected to enhance or depress the relative sensitivities of the achromatic and chromatic systems.

There are no references of which we are aware that have looked directly at the question of depth perception with yellow goggles. However several authors have asked whether chromatic signals play a role in stereopsis (19, 38, 39). The results are somewhat equivocal: some authors have found stereopsis with contours formed of hue variations without luminance differences, while others have not. It is probably safe to conclude that luminance differences are much more important to stereopsis than hue differences. This would be in agreement with our failure to find any effects of yellow goggles on stereopsis.

Theoretical Implications

The model of the visual system that served as an impetus for this research has two major channels conveying information, the achromatic and the chromatic or opponent. A second model with two information channels, the sustained and transient systems, has also been discussed. The data base for the theories has been different, primarily color vision studies, spectral sensitivity and additivity experiments for the achromatic/chromatic theory (3,6,10) and single cell recordings to achromatic stimuli from cat and monkey for the sustained/transient theory (25-27). Nonetheless, there has been the suggestion that the channels in the two models might be identical: usually this suggestion takes the form that the achromatic channel is the same as the transient and the opponent channel is the sustained (7,9). The electrophysiological data on this point are inconclusive. Gouras (26,40) has reported that opponent cells in macaque respond with sustained firing while the achromatic cells give transient responses. Marrocco et al (41,42) however found both achromatic and chromatic responses in both sustained and transient cells. Similarly de Valois (34) reported sustained cells in macaque were of both opponent and non-opponent types.

This suggestion of identity between channels in the two models, while parsimonious and therefore appealing, probably is an oversimplification. A major problem, that has been realized for some time, is raised by the data on acuity. Acuity, or the ability to resolve high spatial frequencies, yields spectral sensitivity and additivity data indicative of the achromatic (transient) system (15,16). However, all the research on the properties of the sustained and transient systems delegates responses to high spatial frequencies to the sustained system. Myers, Ingling, and Drum (16) pointed out this inconsistency and rejected the conclusion that acuity is mediated solely by the achromatic system. Ingling (7,43-45) has published several papers describing more complex models designed to explain the inconsistencies. These data support Ingling in that acuity was not improved by yellow goggles while other spatial frequencies mediated by the sustained system were.

The present status of the chromatic/achromatic model is that in simple form it predicts very well a large body of diverse data on vision and color vision. There are, however, inconsistencies, as have been pointed out, and the details of the model have yet to be decided. Among the important issues are the specific cones contributing to the opponent-color system and the role of adaptation in changing the sensitivities of the opponent system. These data on the effectiveness of yellow goggles both support the general model and add more questions for which the details must be worked out. Prominent among the latter are the changes in the frequency distributions of reaction times which occurred for the low contrast targets of 2 cpd.

Practical Applications

The final, practical consideration is that of the conditions under which yellow goggles might be effective in improving both vision for low contrasts and depth perception. Practical experience and the data from these studies and from the literature suggest that there is an optimum range of light levels.

That this range is within lower photopic levels, is suggested by the data of Everson and Levene (37), by the fact that the dark yellow goggles were generally as effective as the light yellow, and by the choice of yellow by skiers under late afternoon lighting conditions. The determination of the effective range will be the subject of future research. Once determined, however, the optimum range can be achieved by the judicious choice of goggles: bright yellow on dark days and dark yellow, glacier-type, on bright days.

While these results have demonstrated the effectiveness of yellow goggles under certain conditions, we are not satisfied that the paradox has been completely solved. First, the differences between yellow and luminance-matched neutrals were small; practical experience suggests they should be larger. Second, we have not shown yellow to be better than no goggles at all, but only the same. The practical advantage thus would be only for those situations in which some eye protection was necessary. However, Everson and Levene did find conditions for which yellow was better than nothing. Furthermore, we know that theoretically we have not employed the best possible conditions. For example, the use of a large, white surround should be important both theoretically and for its application to snow-covered terrain. However, our use of this feature in the last reaction time experiment was coupled with the oscilloscope whose phosphor is unfortunately deficient in long-wavelength energy, a necessary feature for optimum use of yellow filters.

In summary we believe we have demonstrated that yellow goggles can be effective, and that we can start to explain why, but we do not believe we have elicited the maximum benefit possible.

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